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ISOMER SPECTROSCOPY IN ODD–EVEN Ti ISOTOPES: APPROACHING $N = 40^*$

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Our understanding of the evolution of the shell structure in nuclei far from stability is based on the study of some key nuclei. Nuclei at or next to double shell closures play a special role in this. Presently, a lot of discussion is concentrated on the neutron-rich calcium isotopes, which provide a rich testing ground for various nuclear models with several traditional and new magic numbers. ^{60}Ca is now almost within reach with the most advanced radioactive beam facilities. In order to investigate the evolution of the shell gap at $N = 40$, the configuration of states in the odd-even titanium isotopes up to $N = 37$ (^{59}Ti) have been studied. In order to experimentally access the shell gap at $N = 40$, it is nowadays within the reach of the most advanced facility the investigation of neutron hole configuration states in odd-even titanium isotopes up to $N = 37$, in the ^{59}Ti nucleus. Such states correspond to relatively simple configurations that constitute a challenging testing ground for effective nuclear interactions. The new data obtained in our experiment allows to place the present predictions concerning the shell closure at $N = 40$ in the calcium region on a more solid ground.

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1. Introduction

In ^{68}Ni , the presence of a high-lying 2^+ state with small transition probability to the ground state is a result of the $N = 40$ harmonic oscillator shell gap between the fp shell and the $g_{9/2}$ orbital. This shell gap is reduced as protons are removed in the Fe and Cr isotopes [1]. Collective behavior is caused by quadrupole correlations which favour energetically the deformed intruder states involving the neutron $g_{9/2}$ and $d_{5/2}$ orbitals and proton excitations across the $Z = 28$ subshell gap [2] leading to rather low-lying first 2^+ states and large $B(E2)$ values.

Limited experimental data is still available for the low-spin states in the region of deformation that develops south of ^{68}Ni . The trend of the ratio E_{4^+}/E_{2^+} towards $N = 40$ in the Cr isotopes suggests a transition from spherical (at $N = 32$) to deformed shapes that approach better the gamma-unstable regime rather than the axially deformed one, while the Fe isotopes lie at the $O(6)$ limit between $N = 30$ and $N = 42$ [3]. To better understand the properties of these nuclei, the knowledge of other states at low-excitation energies are needed.

The large difference in angular momentum between the $p_{1/2}$, $f_{5/2}$ and $d_{5/2}$, $g_{9/2}$ orbitals around the Fermi surface in $N \approx 40$ nuclei leads to the occurrence of several isomeric states. In the Cr and Ti, nuclei with $N = 39$ and $N = 41$ similar configurations should also lead to long-lived states. The observation of isomers at $N = 39$ will allow us to draw conclusions on the location and evolution of intruder orbitals towards ^{60}Ca . Theoretical and experimental investigations show that the collective behavior observed in ^{64}Cr , with its small $E(2^+)$ energy and large $B(E2)$ value, is restored approaching ^{60}Ca [2, 4].

In this proceeding, we present some preliminary experimental results on the spectroscopy of the most neutron-rich Ti isotopes. Several new gamma transitions de-exciting isomeric states as well as states populated in the beta decay have been identified for the first time allowing to extend our knowledge of nuclear structure. The determination of beta decay halfives in this region is of relevance for a better understanding of the stellar nucleosynthesis.

A high intensity ^{238}U beam provided by the RIKEN Nishina Center Accelerator Complex impinging on a Be target was used to produce the nuclides of interest in in-flight fission. In the experiment, the EURICA gamma-ray array [5] surrounded the implantation detector AIDA [6] (Fig. 1) into which the fragments of interest were implanted. The fragments were identified using the BigRIPS separator employing the ΔE -ToF- $B\rho$ method. Figure 2 shows the particle identification plots of the fragments using this technique.

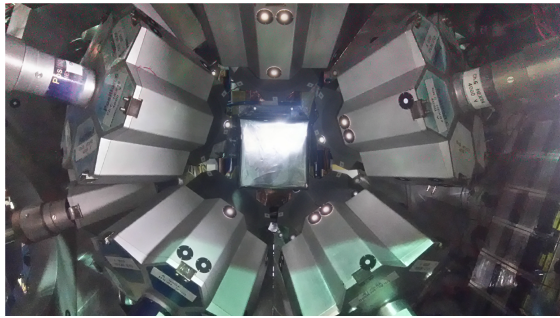


Fig. 1. The EURICA germanium array surrounding the AIDA setup used for the measurement here reported.

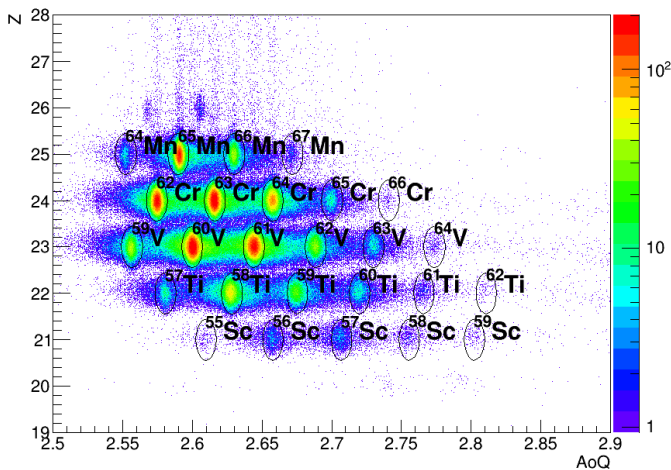


Fig. 2. Ions produced, identified and implanted into the AIDA active stopper.

2. Odd–even Ti isotopes

In this experiment, we populated the ^{59}Ti isotope with much better statistics with respect to previous studies, see Fig. 3. Former experiments identified two isomers in ^{59}Ti , one at 114 keV and one at 699 keV in a study reported by Matea *et al.* [7]. The measured halflife, 600(50) ns, suggested that the 114keV transition would be more likely an E2 transition. The favourite level scheme of ^{59}Ti contains the 699 keV transition feeding the ground state that is not in coincidence relation with the decay of the first isomer at 114 keV. This second isomer was measured a halflife of ≈ 70 ns, corresponding to a M2 transition.

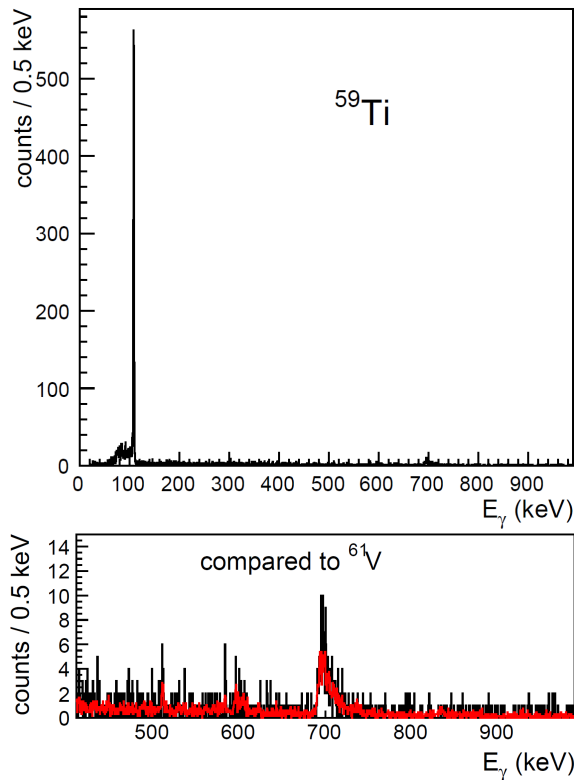


Fig. 3. (Color online) (Top) Isomeric γ decays associated with the implantation of ^{59}Ti nuclei. (Bottom) Zoom on the 400–1000 keV region. The spectrum in gray/red corresponds to the one following the implantation of ^{61}V that is used for the estimation of the background shape. At 699 keV, the spectrum of ^{59}Ti follows the ^{61}V thus not showing any isomeric transition in the region, differently from what was previously reported [7].

Kameda and collaborators reported in 2012 [8] the observation of the lowest isomer in ^{59}Ti at an excitation energy of 109.0 keV with a half-life of 587^{+57}_{-51} ns and the authors proposed an E2 transition from a 109 keV state of spin $(1/2^-)$ to the $(5/2^-)$ g.s. The spins were tentatively assigned based on systematics of ^{55}Ti and ^{57}Ti isotopes, where the re-ordering of single-particle orbitals is assumed with the $\nu 1f_{5/2}$ orbital above the $\nu 2p_{1/2}$ one in agreement with GXPF1A interaction calculations. In particular, this ordering would suggest a spin and parity of $1/2^-$ for ^{55}Ti g.s. [9] and of $5/2^-$ for ^{57}Ti g.s. with a $(1/2^-)$ first excited state [9, 10].

The comparison of the γ spectra obtained for ^{59}Ti and the one from ^{61}V which does not have any known isomer shows that the background recorded in the 600–800 keV region is the same, see Fig. 3. This indicates that the second isomer has not been observed in our experiment despite the similar production mechanism and at least a factor of 20 more statistics for the 109 keV isomer. The structure of the background visible at 699 keV can be accounted for as due to neutron activation of the germanium detectors and we suggest that this was also the case for the experiment previously reported. We, therefore, propose that the second isomer at 699 keV does not exist.

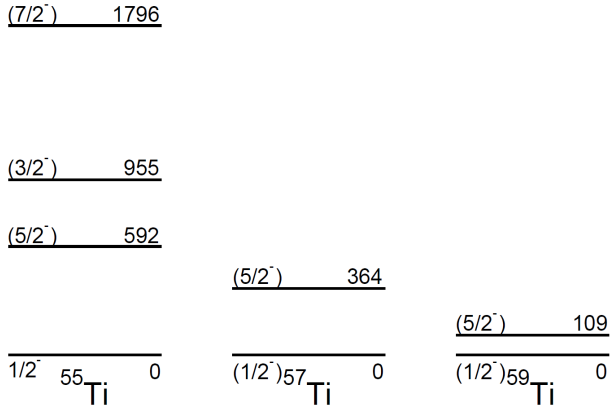


Fig. 4. Lowest lying negative parity states observed so far in odd–even Ti isotopes.

In Fig. 4, the systematics of the lowest lying states is shown for the $^{55,57,59}\text{Ti}$ isotopes. These experimental data and assignments are in agreement with the theoretical calculations obtained using the LNPS interaction that will be presented elsewhere [11]. The results show neutrons particle–hole excitations in the gd orbitals, suggesting that ^{59}Ti lays in the Island of Inversion around $N = 40$. The calculations are compatible with the experimental findings and, therefore, we propose to assign $J^\pi = (1/2^-)$ to the ground state and $J^\pi = (5/2^-)$ to the isomer in ^{59}Ti .

In the ^{57}Ti , the situation is similar. Two low-lying negative parity states are known experimentally [9]. Originally, the ground state had been assigned $J^\pi = 5/2^-$ with an excited $1/2^-$ state based on comparison with the GXPF1 interaction [12]. This ordering is reversed with the improved GXPF1A effective interaction [13] as well as with the LNPS interaction [11]. This suggests a change of the spin assignments to $J^\pi = (1/2^-)$ for the ground state and $(5/2^-)$ for the first excited state. This assignment also agrees with the observed large feeding in the decay of the $J^\pi = 7/2^-$ ground state of ^{57}Sc to the excited state at 364 keV of ^{57}Ti . The ground states of both $^{55,57}\text{Ti}$ isotopes are dominated in the LNPS calculations by fp configurations, with marginal excitations to the gd orbitals, which locates these isotopes outside the $N = 40$ Island of Inversion.

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